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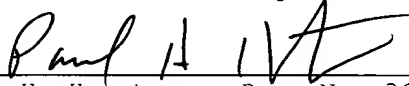
MOTION CONTROL
USING TIME SYNCHRONIZATION

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BACKGROUND OF THE INVENTION

Field of Invention

5 The present invention pertains to the field of systems. More particularly, this invention relates to motion control using time synchronization technology.

10 Art Background

 Motion control systems are commonly employed in a wide variety of devices and systems including devices and systems used in industrial, office, and home environments. A motion control system may be defined as a control system that provides precise control of the movement of various actuating elements of a device or system. A controllable movement of an actuating element may be referred to as an axis or a degree of freedom. A typical motion control system includes an actuator for each axis and control circuitry that generates control values and provides the control values to the actuators as needed for a desired motion.

25 For example, a pen-based plotter usually includes an actuating element that moves a pen along an x axis and an actuating element that moves the pen along a y axis and these actuating elements provide two degrees of freedom for pen movement. Other degrees of freedom for pen movement in a plotter may be provided by actuating elements that change ink colors and actuating elements that move the pen into and out of contact with paper.

Prior motion control systems typically include a central controller which generates control values and provides the control values to the actuators in a sequence that will accomplish a desired motion. It is usually desirable that the control values be applied to the actuators with precise timing in order to precisely coordinate the motion among the axes. Any delay or skew in the application of control values to different actuators may cause deviation from the desired motion.

For example, a central controller in a plotter typically generates a series of x control values and a corresponding series of y control values when drawing a circle. It is usually desirable that each x control value be applied to the x actuator at the same time as the corresponding y control value is applied to the y actuator in order to prevent one axis or the other from deviating from the desired circle motion.

Prior motion control systems usually accomplish such precise coordination in the application of control values by employing control cards that enable the simultaneous application control values to multiple actuators. For example, a control card may have two output registers for applying control values to two different actuators. A central controller in such a system usually loads the output registers and then simultaneously triggers the outputs of both of the output registers to the actuators at the desired time. The tight coupling of the output registers on a card usually ensures that the corresponding control values are applied at substantially the same time.

Typically, such control cards are manufactured in standard numbers of axis, such as 2 or 4 axis, in order to be cost effective. If coordination is needed among more axes than a standard number then
5 several cards may be necessary and some scheme must usually be devised for coordination among the cards. In addition, if portions of a motion control system are widely separated then coordination of the remote portions usually requires special attention to wiring
10 or the use of specialized networks for communication among such prior control cards. Unfortunately, this usually increases the cost and complexity of a motion control system. On the other hand, fewer axes may be needed for a motion control system than are provided
15 on such a prior control card. In that case the extra hardware purchased but not used usually adds unneeded costs to a motion control system. In addition, such prior control cards may make it difficult to upgrade a system if existing control cards cannot accommodate
20 additional degrees of freedom.

SUMMARY OF THE INVENTION

5 A motion control system is disclosed having a
set of control nodes each of which controls motion
along a single axis of the motion control system and
which coordinate their collective motions using time
synchronization technology. Each control node
corresponds to an axis of the motion control system
and each control node includes a synchronized clock
10 and participates in a protocol for synchronizing the
synchronized clocks. The application of a series of
control values to each axis in the motion control
system is coordinated using the synchronized clocks.

15 A motion control system based on time
synchronization enables the use of simpler and
cheaper computing resources in each control node in
comparison to prior systems in which one control card
must handle multiple axes simultaneously. Each
20 control node may be sized and optimized for the
characteristics of a particular axis as well as the
motion function to be implemented. Only the exact
number of control nodes used in motion function are
used and extra capacity is not wasted. A motion
25 control system based on time synchronization enables
the use of a conventional network communication link
for clock synchronization rather than a specialized
higher cost link that might otherwise be needed to
coordinate motion control as may be the case prior
30 systems.

Other features and advantages of the present
invention will be apparent from the detailed
description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described with respect to particular exemplary embodiments thereof and
5 reference is accordingly made to the drawings in which:

Figure 1 shows a motion control system for a device according to the present techniques;
10

Figure 2 shows one embodiment of a control node which includes a time packet recognizer;

Figure 3 shows a motion control system which
15 includes a selector node.

DETAILED DESCRIPTION

Figure 1 shows a motion control system for a device 10 according to the present techniques. The motion control system includes a set of control nodes 30-34 each of which controls motion along a single axis of the motion control system by driving one of a set of actuators 20-24 of the device 10. Each control node 30-34 includes a corresponding synchronized clock 40-44 which holds a synchronized time value. The control nodes 30-34 coordinate the motions among the axes of the device 10 using the synchronized clocks 40-44.

The control nodes 30-34 participate in a synchronization protocol for synchronizing the time values held in the synchronized clocks 40-44. The synchronization protocol is provided so that the synchronized clocks 40-44 hold time values that agree to an accuracy suitable for coordinating the motions among the axes of the device 10.

The control nodes 30-34 apply sets of control signals 50-54 to the actuators 20-24 to perform a motion control function associated with the device 10. Each control node 30-34 associates a series of control values to be applied to the corresponding actuator 20-24 to a time value according to the motion control function. The applications of the control signals 50-54 to the actuators 20-24 by the control nodes 30-34 are triggered by synchronized time values obtained from the synchronized clocks 40-44. Each control node 30-34 monitors its corresponding synchronized clock 40-44 to determine

when to apply a control value to its corresponding actuator 20-24.

5 The device 10 represents any type of device or any type of mechanical, electrical, chemical, or combination system in which precise coordination of the application of control signals to the actuators 20-24 is desirable. Examples are numerous and include printers, plotters, and manufacturing systems
10 found in a wide variety of industries.

15 The following discussion focuses on an example embodiment in which the device 10 is a plotter in which the actuator 20 controls the x position of a pen and the actuator 22 controls the y position of the pen and the actuator 24 controls the up/down status of the pen. It is apparent, however, that the teachings provided with respect to the example embodiment are readily applicable to a variety of
20 other devices and systems including very complex systems with many more axes. In fact, one advantage of the present techniques is that very complex systems may be arranged into a distributed control system with relatively simple low-cost control nodes and an accurate synchronized time base that provides
25 coordination among many axes of motion.

30 The control nodes 30-34 in the example embodiment may implement a motion control function for drawing a circle in which the control nodes 30-32 use the actuators 20-22 to move the x and y positions of the pen along the x and y axes according to the following equations.

Eq. 1 $x = \cos \omega t$

Eq. 2 $y = \sin \omega t$

5 The x and y positions yielded by equations 1 and
2 provide the control values to be applied to the
actuators 20-22 via the control signals 50-54. The
control nodes 30-32 may compute the x and y control
values in real-time for a predetermined series of t
values using equations 1 and 2 or the x and y control
10 values may be pre-computed for the predetermined
series of t values and stored in tables in the
control nodes 30-32. The predetermined series of t
values provide trigger times for applying the
corresponding x and y control values to the actuators
15 20-22.

Assume for example that at time t_0 the control
node 30 is to move the pen to position x_0 along the x
axis and that the control node 32 is to move the pen
20 to position y_0 along the y axis in accordance with
equations 1 and 2. The control node 30 monitors the
synchronized clock 40 and when it reaches t_0 applies
the control value x_0 to the actuator 20 to move the
pen to position x_0 . Similarly, the control node 32
25 monitors the synchronized clock 42 and when it
reaches t_0 applies the control value y_0 to the
actuator 22 move the pen to position y_0 . The precise
coordination in movement along the x and y axes is
accomplished by the precise synchronization of the
30 synchronized clocks 42-42 in triggering on the t_0 time
value.

A motion control system using the control nodes
30-34 each of which provides motion control for a

single axis enables the use of simpler and cheaper computing resources in each control node 30-34 in comparison to prior systems in which a single control card handles multiple axes. Each control node 30-34
5 may be sized and optimized for the characteristics of a particular axis as well as the motion function to be implemented in that axis. Only the exact number of the control nodes 30-34 needed for the particular number of axes of motion is required and extra
10 capacity is not wasted.

In one embodiment, the protocol and related mechanisms for synchronizing the time values held in the synchronized clocks 40-44 are those described in
15 U.S. Patent no. 5,566,180. For example, each of the synchronized clocks 40-44 may include circuitry for adjusting its respective locally stored time value based upon computations of the sending and receiving time of time data packets which are transferred over
20 a communication link 12. This protocol provides accurate clock synchronization at a relatively low cost with a relatively low bandwidth utilization on the communication link 12.

25 The communication link 12 may be implemented with one or more of a variety of communication mechanisms. The coordination of motion control provided by the synchronized clocks 40-44 and the synchronization protocol enables the use of a
30 conventional network communication link for the communication link 12 rather than a specialized higher cost link that might otherwise be needed to coordinate motion control among prior control cards that control multiple axes. In one embodiment, the

communication link 12 is an Ethernet communication network. In another embodiment, the communication link 12 is a LonTalk field-level control bus which is specialized for the process control environment. In
5 other embodiments, the communication link 12 may be implemented with time division multiple access (TDMA) or token ring protocols to name only a few possibilities.

10 **Figure 2** shows one embodiment of the control node 30. The control nodes 32-34 may be implemented in a substantially similar manner. The control node 30 includes a processor 60 that implements a motion control function associated with the device 10. The
15 processor 60 associates each control value to be applied to the actuator 20 to a time value. The processor 60 may perform the associations on the fly using motion control calculations or may pre-compute the associations or the associations may be pre-
20 computed and stored in a table for subsequent reading by the processor 60 when applying control values to the actuator 20.

The control node 30 includes a physical
25 interface 64 to the communication link 12 and a time packet recognizer 62 that exchanges timing data packets and follow up packets with the nodes 32-24 according to the protocol for synchronizing the time values held in the synchronized clocks 40-44.

30

For example, the time packet recognizer 62 generates a first timing data packet and transfers it via the communication link 12 through a physical interface 64. At the time that the time packet

recognizer 62 transfers the first timing data packet to the physical interface 64 it samples the synchronized clock 40 to obtain a first time-stamp. The first time-stamp indicates the local time in the control node 30 at which the time packet recognizer 62 transferred the first timing data packet to the physical interface 64. Thereafter, the time packet recognizer 62 generates a follow up packet and transfers it via the communication link 12. The follow up packet includes the first time-stamp. The control nodes 32-34 receive and time stamp the first timing data packet generated by the control node 30. The control nodes 32 then receive the follow up packet and use the differences between the first time stamp contained in the follow up packet and the time stamps associated with the reception of the timing data packet to determine any adjustments needed for the synchronized clocks 42-44.

Similarly, the time packet recognizer 62 receives a second timing data packet generated by one of the control nodes 32-34 through the physical interface 64. The time packet recognizer 62 latches a local time value from the synchronized clock 40 when the second timing data packet is received and this latched time value provides a time stamp for reception of the second timing data packet. Thereafter, the time packet recognizer 62 receives a follow up packet from the control node 32-34 that originated the second timing data packet. The time packet recognizer 62 extracts a second time-stamp from the follow up packet. The difference between the time-stamp from the follow up packet and the time stamp for reception of the timing data packet

indicates the relative adjustment needed for the
synchronized clock 40 to maintain synchronization
among the synchronized clocks 40-44. The difference
may be computed by the processor 60.

5

The synchronized clock 40 is implemented as a
counter driven by an oscillator with sufficient
stability. The least significant few bits of the
counter may be implemented as an adder so that the
10 increment on oscillator periods may be occasionally
increased or decreased to effectively speed up or
slow down the synchronized clock 40 in accordance
with the results of the computation of difference
between time stamps for timing data packets and the
15 corresponding time stamps contained in follow up
packets.

The processor 60 obtains synchronized time
values from the synchronized clock 40 and uses the
20 synchronized time values as triggers for providing a
series of control values to a digital-to-analog (DAC)
converter 66. For example, a motion control function
with respect to the control node 30 may be defined as
shown in table 1.

25

Table 1.

Δt values	control value
0.010	2
0.020	3
0.025	4
0.030	5

5

10 The Δt values are time values relative to a t_0
time value. Each Δt value is associated with a
control value to be applied to the actuator 20. For
example, a control value of 2 is to be applied at
time $t_0 + 0.010$ and a control value of 3 is to be
applied at time $t_0 + 0.020$. The processor 60 monitors
15 the synchronized clock 40 and when it reaches time t_0
+ 0.010 writes a control value of 2 to the DAC 66.
Similarly, the processor 60 monitors the synchronized
clock 40 and writes a control value of 3 to the DAC
66 when the synchronized clock 40 reaches time $t_0 +$
20 0.020.

25 The control nodes 32-34 perform their portion of
the motion control function in concert with the
control node 30 using control values associated with
time values. For example, the control nodes 32-24
may each have a table of control values to be applied
at Δt intervals relative to a t_0 . The control nodes
32-34 monitor their respective synchronized clocks
42-44 and apply their respective control values at
30 Δt intervals to maintain coordination with the
application of control values by the control node 30.

The DAC 66 provides analog control signals to signal processing 68 which in turn drives the control signals 50 to the actuator 20. In other embodiments, the control node 30 may provide digital control values to the actuator 20 via the control signals 50 and the actuator 20 may contain the DAC 66 and signal processing 68.

The processor 60 and its related resources may be scaled according to the particular motion control function being implemented and timing requirements etc. For example, if the processor 60 must calculate control values on the fly using relatively complex motion equations and/or must calculate control values during very brief time intervals then a relatively powerful processor may be needed along with sufficient memory resources. On the other hand, if the equations for motion control are relatively simple or pre-computed or if the time intervals for calculating control values is relatively long, i.e. for relatively slow motion, then simpler and lower cost processor and memory resources may be used thereby lowering the cost of the control node 30.

Figure 3 shows a motion control system for the device 10 which includes a selector node 14. The control nodes 30-34 include corresponding sets of tables $1-n_1$, $1-n_2$, and $1-n_3$, respectively. Each of the tables $1-n_1$, $1-n_2$, and $1-n_3$ holds a set of control values to be applied to the corresponding actuators 20-24. Each control value in the tables $1-n_1$, $1-n_2$, and $1-n_3$ is associated with a time value which is to be used to trigger the application of the control value as previously described.

The control values in any one or more of the tables $1-n_1$, $1-n_2$, and $1-n_3$ may be pre-computed by the selector node 14 and distributed to the control nodes 30-34 via the communication link 12. Alternatively, 5 the control values in any one or more of the tables $1-n_1$, $1-n_2$, and $1-n_3$ may be pre-computed by the processor resources in the corresponding control node 30-34. The selector node 14 may distribute equations to the control nodes 30-34 via the communication link 10 12 that enable the control nodes 30-34 to pre-compute the control values for the corresponding tables $1-n_1$, $1-n_2$, and $1-n_3$.

The selector node 14 may determine a motion 15 control function to be applied to the device 10 by transferring messages to the control nodes 30-34 via the communication link 12 that specify which of the tables $1-n_1$, $1-n_2$, and $1-n_3$ is to be used and that specify a starting time t_0 for the motion control 20 function. For example, the selector node 14 may transfer a message to the control node 30 which specifies that table 1 in the control node 30 is to be applied starting at 2 PM and may transfer a message to the control node 32 which specifies that 25 table 3 in the control node 32 is to be applied starting at 2 PM. In response, the control nodes 30-32 monitor their respective synchronized clocks 40-42 and begin applying the specified control values when their respective synchronized clocks 40-42 reach 2 30 PM.

Alternatively, the selector node 14 may determine a motion control function to be applied to the device 10 by transferring messages to the control

nodes 30-34 via the communication link 12 that contain equations for generating a table of control values to be used and that specify a starting time t_0 for the motion control function. For example, the selector node 14 may transfer a message to the control node 30 which specifies that x control values derived from $x = \cos \omega t$ are to be applied starting at 2 PM and may transfer a message to the control node 32 which specifies that y control values derived from $y = \sin \omega t$ are to be applied starting at 2 PM. In response, the control nodes 30-32 pre-compute the control values using these equations and then monitor their respective synchronized clocks 40-42 and begin applying the pre-computed control values when their respective synchronized clocks 40-42 reach 2 PM.

In another alternative, the selector node 14 may determine a motion control function to be applied to the device 10 by transferring messages to the control nodes 30-34 via the communication link 12 that contain pre-computed control values and associated time values and that specify a starting time t_0 for the motion control function.

The foregoing detailed description of the present invention is provided for the purposes of illustration and is not intended to be exhaustive or to limit the invention to the precise embodiment disclosed. Accordingly, the scope of the present invention is defined by the appended claims.